

## EVOLUTION OF THE VICTORIAN COASTLINE

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**ABSTRACT:** The history of the Victorian coastline can be traced back to the Late Cretaceous and its evolution is closely related to the development of the Eastern Highlands. Superimposed on local and regional earth movements are glacio- and tectono-eustatic sea level fluctuations. The shore zone has migrated between the outer edge of the continental shelf and the upland front.

Former correlations and interpretations are questioned, particularly with regard to the Gippsland Lakes area, and previously unreported Quaternary marine sediments from the Peterborough coast are briefly described. Tertiary shoreline and shoreline-related features in southern Victoria are more widely represented than previously thought and provide important local physiographic control in some areas.

The Quaternary shore, except in far southwestern Victoria, did not migrate inland far beyond the present coast, implying considerable earth movement during that time.

Radiometric dating of coastal features, sedimentary facies analysis, detailed topographic surveys and a reliable global stratigraphic scale are required for the detailed elucidation of Victorian coastal history.

### INTRODUCTION

The coast is a zone of interaction between marine and terrestrial forces, the nature and intensity of which control the kinds of landforms produced and the types of deposits formed. The Late Cretaceous Victorian coast formed the inner margin of a series of partially interconnected marine basins which commenced as broad downwarps during Early Cretaceous times. However, the maximum marine incursion occurred at different times in different basins.

The basins owe their general shape directly to tectonics, but shorelines have varied throughout their history in response to changes in the relative levels of land and sea. The tectonic movements were of two kinds: broad, epeirogenic uplift and downwarping, and local movements related to sharply defined structural lineaments (Fig. 1). Earth movement was an important determinant of relative sea level, but upon this were superimposed fluctuations in the actual level of the sea itself.

Former coastal zones may be represented by erosional and depositional landforms as well as characteristic deposits. The recognition of former coastal features in Victoria is still controversial, just as the relative importance of tectonics and glacioeustasy in sea level change remains open to debate.

Current views on these points are discussed below and some possible alternative interpretations of Victorian sequences suggested.

### RETREATING SHORELINES OF THE LATER TERTIARY

The retreat of the sea from the Tertiary basins occurred in the Late Miocene to Pliocene, although some local readvances have been recorded (Abele, *et al.* 1976). In the Murray Basin the uppermost marine sediments are a sheet of silts and sands, the upper surface of which is ridged by a series of subdued to prominent, sub-parallel elongate rises (Fig. 1). The more prominent ridges were recognised by Hills (1939) who suggested that they were reflections of faulting and warping in the underlying bedrock. Subsequently, it was proposed that the ridges represented stranded coastal dunes (Blackburn 1962). Although these ridges cannot be accepted in all cases as former dunes, owing to the frequent coarseness of the sediments and the sub-aqueous nature of the bedding, it is now accepted that they represent stranded shoreline features, the precise nature of which has yet to be determined (Lawrence 1966, 1975, 1976, Bowler & Magee 1978).

ERTS imagery indicates the multiplicity of these features (Fig. 1), data which were not available to

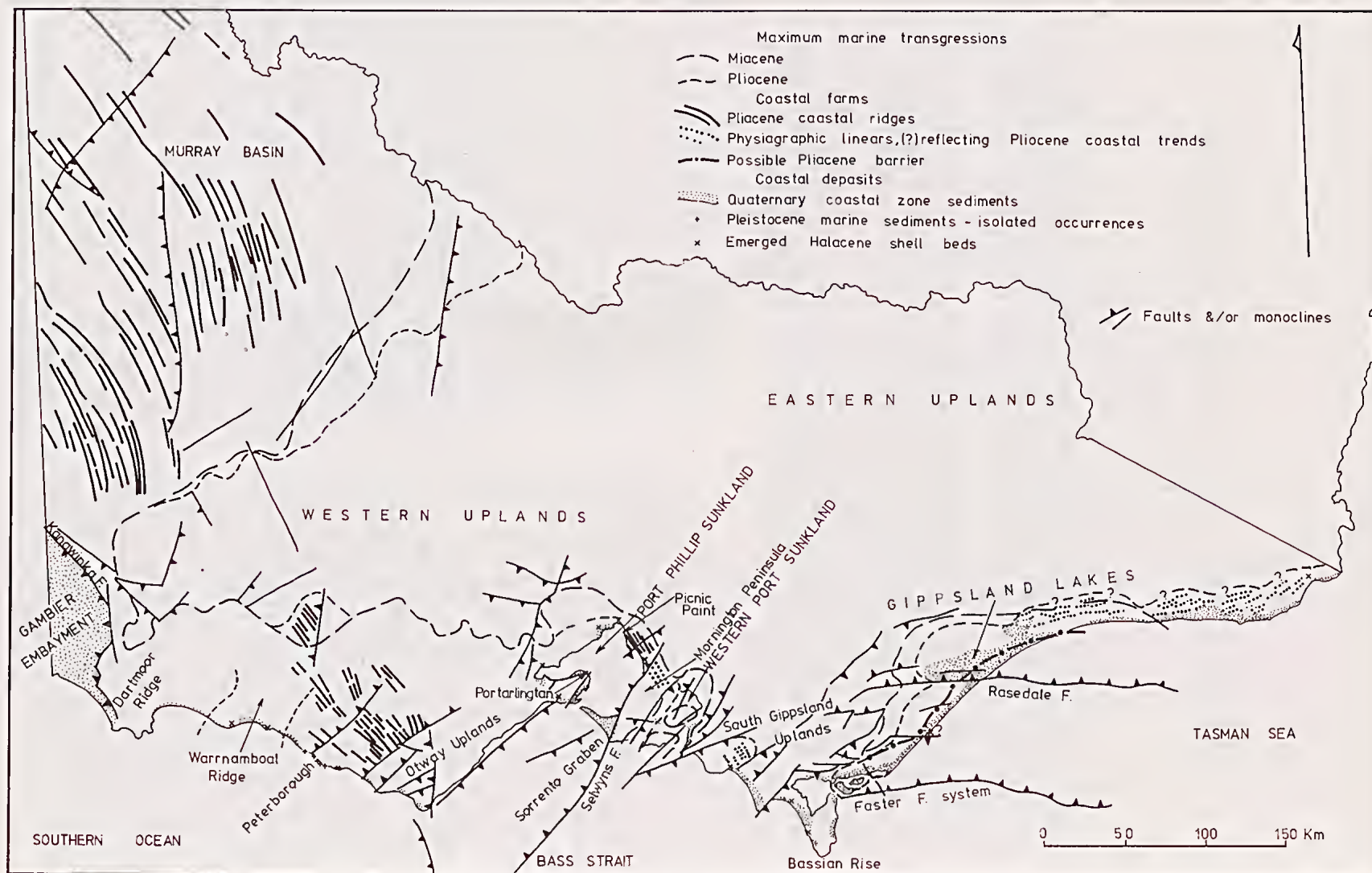


FIG. 1—Victorian coastal features in relation to geological structure.



the earlier workers. Ridges of this type are not confined to north-western Victoria. In the Otway Basin, they are also displayed on Late Tertiary sediments which survive as "windows" within the Volcanic Plains. Towards the Otway Ranges a similar parallelism appears in the deeply dissected valleys (Fig. 1). Satellite imagery indicates the possibility that the parallel interfluves represent the sites of former shoreline features and that the streams followed the inter-ridge troughs, deeply dissecting them during subsequent uplift. The dissection observed on the upthrown blocks is lacking on adjacent lower blocks, although ridge and valley trends are maintained from one area to the other. Even though the deposits which have been preserved are fragmentary, their nature suggests shallow water, probably shore zone deposition. At least two distinct depositional environments are indicated. The coarser sediments exhibit gently seaward-dipping laminae and steeper landward-dipping beds, while the silts and clays are abundantly burrowed, suggesting turbulent and sheltered shore zone conditions respectively. These deposits are regarded as being westerly equivalents of the Moorabool Viaduct Formation, the age of which varies from Early to Late Pliocene (Abele *et al.* 1876, Douglas 1977).

The ridges are intersected by the dominant north-easterly tectonic trend, their transverse displacement on faults being clearly seen on ERTS photographs. In addition, the division between the parallel interfluves of the deeply dissected area and the gentle ridge and swale terrain is very sharply defined by the well-established Curdie and Colac Faults. The ridge trends are straight or slightly concave towards the southwest and there is a slight change in direction between the central fault block and the blocks on either side. Within the two easterly blocks themselves, there is a change in direction of the ridges from north-north west to northwest as the sea is approached, although the trend of the innermost group of ridges is more towards the northwest and continuous across the projected continuation of the Curdie Fault. The changes in trend would be consistent with skewed tilting of the fault blocks during uplift of the land and associated retreat of the sea.

In the western part of the Port Phillip Sunkland, which occupies the eastern end of the Otway Basin, the Moorabool Viaduct Formation has a non-marine component, although its extent is not known, and the undoubted marine deposits were of shallow water origin (Bowler 1963). Some of these deposits in the Geelong area are regarded as intertidal and to have been deposited in an east-

west strait (Doust 1968), but no shoreline features as such have been identified.

On the Brighton coastal plain, on the northeast side of Port Phillip, there is a series of low parallel ridges forming the upper surface of Late Tertiary shallow water marine sediments. The ridges, once thought to be tectonic, are now accepted as being depositional features (Kenley 1967, Vandenberg 1971). It seems likely that the ridges are shore features similar to those on the Port Campbell coastal plain. In addition, there is a continuity of trend with the ridges south-east of the Beaumaris Monocline, through the Carrum Swamp area, to the Cranbourne Sand ridges of the northern part of the Mornington Horst. It is suggested therefore that a genetic relationship may exist between the sandy ridges of the Brighton Coastal Plain, the Carrum Swamp area and the Mornington Horst, these respectively being little modified, partially blanketed by alluvial and swamp deposits and extensively wind modified, probably during the Pleistocene.

Further east, in the area north of Inverloch, towards the South Gippsland Uplands there is an extensive area of Tertiary ferruginous sands and clays which show a very distinct northwest-trending, subdued ridge and intervening swamp terrain. This is a pattern more akin to a progressively retreating coast than that which would be expected in outwash fans from the adjacent uplands, or to have developed on emerged sub-aqueous beds, nor can the pattern be satisfactorily explained by tilting.

On the coastal plateau east of the Gippsland Lakes (the piedmont fringe of Talent 1969) there are marked alignments in the tributary drainage parallel to the present coast (Fig. 1). These trends intersect the dominant structural grain and appear on Tertiary clastic sediments of varying texture, some of which have been extensively ferruginised. The trends also appear on Palaeozoic sedimentary rocks and granites which carry scattered residuals of Tertiary sediments and may represent a superimposed drainage pattern.

A coastal origin, or at least influence in the formation of these ridges and trends particularly those of southern Victoria, has not been established with certainty, but their apparent independence of direct structural control and their alignment parallel to the present coast, and normal to the dominant swell approach implies such a relationship. The varied composition of the sediments does not suggest a dune origin for the ridges, although aeolian reworking of older sediments may account for the strong alignments



in the Cranbourne Sand deposits between Port Phillip and Western Port, and the dunes overlying the Moorabool Viaduct Formation on the Bellarine Peninsula. The wide separation of the Cranbourne Sand ridges seems to preclude normal transverse dune formation, and longitudinal dune formation is most unlikely, assuming that the dominant wind direction has not changed markedly through later Cainozoic time.

Undoubtedly, the later Tertiary deposits in southern Victoria call for detailed study, especially in geomorphic context, in view of their obvious physiographic importance in relatively elevated coastal areas.

In lower-lying regions, such as the Gippsland Lakes—Latrobe Valley depression, the Tertiary marine sediments are usually blanketed by Quaternary deposits. In this area, although the limits of Tertiary marine sedimentation have been defined from subsurface data and sporadic outcrop, little is known concerning the precise nature of the coastal environments. On Mississippi Creek, to the north of Lakes Entrance, the edge of the Early to Middle Miocene Gippsland Limestone appears as a boulder and gravel bed, with abundant shells, transgressing the granite bedrock, undoubtedly a beach or near shore deposit. Highly ferruginised shelly beds also occur near the Brodribb River, east of Orbost, closely defining the Miocene coastline in this area. Further west, in the axis of the Latrobe Depression, deposition of the marine Gippsland Limestone and the terrestrial Morwell and Yallourn Formations continued synchronously (Abele *et al.* 1976) but the detailed inter-relationships between the two is uncertain. The Late Miocene (Tambo River) and Early Pliocene (Jemmys Point) formations represent a regressive phase following the maximum Middle Miocene (Gippsland Limestone) transgression. In the Lake Wellington area the beds between the wholly marine Jemmys Point Formation and the overlying non-marine Boisdale Formation appear to be transitional near-shore deposits. Their facies similarity to Recent deposits in Lake Reeve was noted by Jenkin (1968) who suggested that tidal flats, lagoons and barriers were present at that time. The view that these beds are late transgressive phases of the otherwise regressive Jemmys Point Formation (Hocking 1972, 1976) is consistent with this interpretation. Beds overlying the Jemmys Point Formation near Lakes Entrance have been described as lagoonal (Wilkins 1963), implying the presence of a seaward barrier, and recently a sandy sheet lying between the undoubted marine section of the Jemmys Point For-

mation and the overlying, supposedly estuarine beds has been interpreted as a barrier remnant (Carter 1979). Succeeding the estuarine beds is a second sand body, also believed to represent a Pliocene barrier, which interdigitates on the landward side with supposed lacustrine sediments.

Although the sands undoubtedly indicate near shore conditions, there is as yet insufficient information to define precisely the forms represented. From the evidence, the sands could be sand tongues or shoals (in the terminology of Reineck & Singh 1975) rather than barriers in the true sense, or both forms may be present contemporaneously or in succession. Nevertheless, there have undoubtedly been changes in relative sea level in the Gippsland Lakes area during the Pliocene. These have been attributed to eustatic sea level fluctuation (Carter 1979).

In general, regressive deposition was dominant in southern Victoria during Late Miocene and Pliocene time, although several readvances have been recorded (Hocking 1976, Abele *et al.* 1976, Carter 1979). In the Murray Basin however, a distinct transgression occurred during the Late Miocene and Early Pliocene, to be followed by continuous regression through the remainder of the Pliocene. These advances do not appear to be contemporaneous and probably occurred over different time spans in different areas; in the Port Phillip basin from Late Miocene into the Early Pliocene, in South Gippsland during the Early Pliocene and in East Gippsland during Mid and Late Pliocene.

There is little doubt that the relative changes in Late Tertiary sea level in Victoria have been influenced by differential earth movements in addition to eustatic effects. World-wide comparisons also suggest the dominance of regression through most of the Pliocene (Fleming & Roberts 1973), but the evidence for widespread synchronous advances during that period is ambiguous.

#### THE PLIO-PLEISTOCENE BOUNDARY

Late Pliocene to Pleistocene marine deposition is rare in on-shore southeastern Australia, except perhaps in the western part of the Otway Basin where the Coomandook and Whalers Bluff Formations were deposited in shallow embayments. However the deposition was diachronous, becoming progressively younger and thicker towards the west (Kenley 1971, Abele *et al.* 1976), while being interrupted on the eastern side by the Greenwald-Cobboboonee Basalt (2.2–3.1 m.y.). The Plio-Pleistocene boundary is taken at 2 million years B.P. (Lambert 1971). Kenley (1976) used 1.8 m.y.,



following the 1948 INQUA definition, and judged by the K-Ar datings on Victorian basalts (Abele *et al.* 1976), this does not affect the generalisations outlined above.

Elsewhere in Victoria, except perhaps in the Sorrento Graben and the Otway and Gippsland offshore areas, there seems to have been a cessation of marine deposition following the Early Pliocene and extending into the Early Pleistocene. Initially this was marked by widespread deep weathering (lateritisation). If this palaeosol is not diachronous, and was formed during a short period, it would be a reliable and, because of its widespread occurrence, useful approximate indicator of the Pliocene-Pleistocene boundary. The youngest deposits affected appear to be Late Pliocene (Moorna Formation, Gill 1966). However it is possible that this formation is equivalent to the Early Pleistocene Blanchetown Clay of the Murray Basin (Lawrence 1976). Elsewhere, the lateritisation is confined to Late Pliocene or older formations. On the Port Campbell coastal plain a similar soil formation has been called the Timboon Pedoderm and equated with similar occurrences in northwestern Victoria (Gill 1973b).

The intensity of the weathering seems to have diminished eastwards from Western Port, although in far East Gippsland deep lateritic profiles have been recorded (Talent 1969). In the Gippsland Lakes area, the most intense ferruginisation affects the top of the Boisdale and Coongulmerang Formations, and should not be confused with local massive ironstones and weaker general oxidation in the Haunted Hill Gravel (Jenkin 1968).

There is little doubt that deposits resting on this widespread pedoderm, or on landforms cut into it, are Late Pliocene or Quaternary in age. It is therefore a useful datum in relation to the fragmentary younger marine deposits along the present coast, for example those lying at a high level at the seaward edge of the Port Campbell coastal plain, and which do not contain diagnostic fossils.

#### PLEISTOCENE CONDITIONS

The early Pleistocene sea, at its maximum extent in south-western Victoria, reached the foot of the Kanawinka scarp, and it was during this period that the greater part of the Whalers Bluff Formation was deposited (Kenley 1976). The subsequent retreat resulted in the stranding of successive subparallel calcareous aeolianite dunes and coastal barriers, collectively known as the

Bridgewater Formation (Boutakoff & Sprigg 1953, Boutakoff 1963, Kenley 1976). Similar aeolianite ridges occur in the embayment east of Portland and at Warrnambool, where Gill (1967, 1976), and Gill & Gill (1973), have described a succession of aeolianites thought to represent early, mid and late Pleistocene interglacials. The oldest, or "early" aeolianite is the highest of the series, and has been tentatively dated at 700,000 years B.P. The position of the innermost Pleistocene shoreline in south-western Victoria can therefore be plotted with some assurance.

Further east, in the Peterborough-Port Campbell area, high-level terraces along the sides of the Curdie and Port Campbell estuaries may be related to Pleistocene high sea levels, although the only definite marine or coastal deposits occur as remnants close to the present coast. In the Port Phillip Sunkland coastal features may, on the basis of field relationships and with some certainty, be referred to the earlier Pleistocene. Shelly sands and gravels at Portarlington were considered by Jutson and Coulson (1937, 1940) to be early Pleistocene, and the easternmost aeolianites of the Bellarine Peninsula (Jenkin 1968, 1974) may be of a similar age. The only specific date relates to the Fishermens Bend Silt in the Yarra Delta which, deposited in a shallow marine embayment, is about 800,000 years old (Neilson 1976).

In Western Port it is unlikely that marine sediments of Pleistocene age are present (Marsden & Mallett 1975), and fluvial activity was dominant. In south-east Gippsland extending from Corner Inlet to Lakes Entrance, there is considerable doubt concerning the identification and age of the supposedly marine Pleistocene forms and deposits, the only undoubted occurrences terminating at former cliffs behind the Inner Barrier, or being represented by shell beds in estuarine and deltaic areas.

#### SEA LEVEL CHANGES

Changes in the relative levels of land and sea in Victoria have been established by many workers, and interpretations have been based on glacioeustasy, local tectonics, or combinations of both.

The occurrence of Plio-Pleistocene sediments of undoubted marine origin and the overlying succession of dune ranges at successively lower levels in south-western Victoria, interpreted as marking still stands during the retreat of the Pleistocene sea, indicate an overall fall in relative sea level of about 65 metres over that period (Boutakoff 1963,

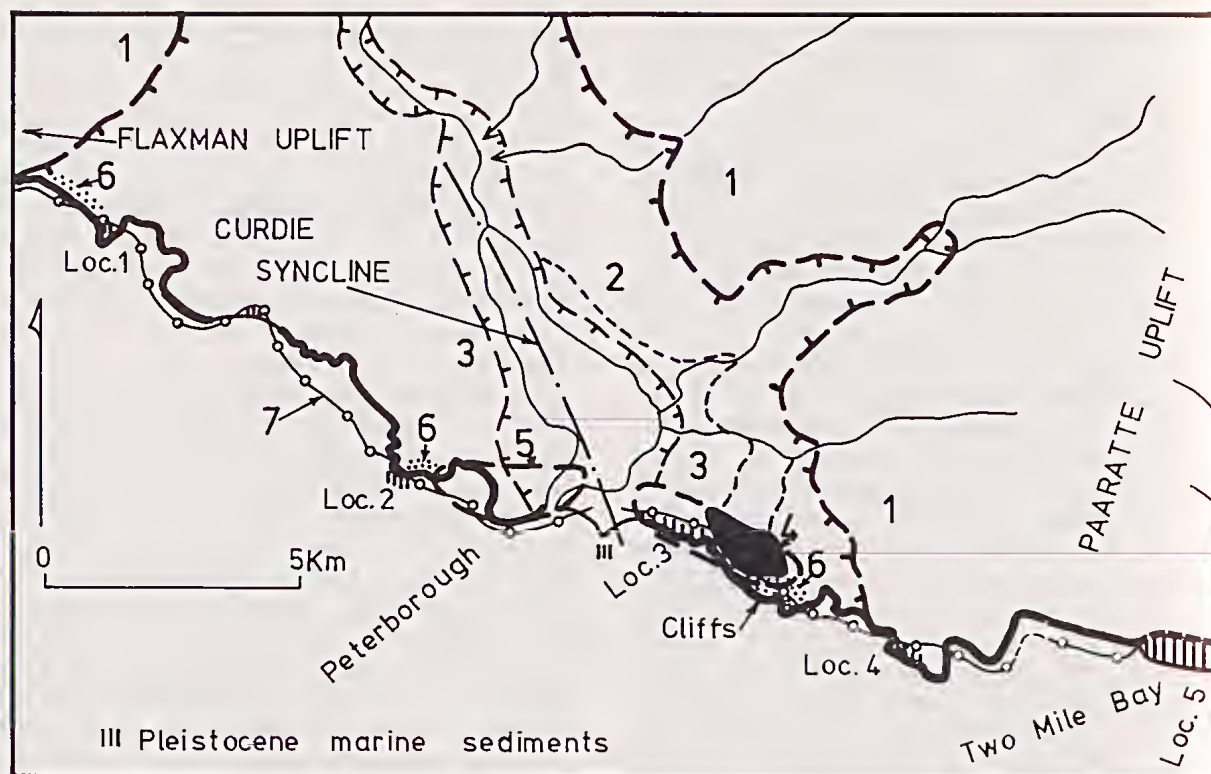


FIG. 2—The coast near Peterborough, western Victoria:

1—High; 2, Intermediate and 3, Low terraces; 4, Aeolianite; 5, Possible original extent of aeolianite; 6, Red-brown cliff-top dunes; 7, Limit of Pleistocene marine sediments.

Kenley 1971, 1976). Breaching and truncation of previously formed dunes during glacioeustatic rises of sea level have also been suggested (Kenley 1976). In the south-east of South Australia a similar series of ridges has been described (Hossfeld 1950, Sprigg 1952, Boutakoff & Sprigg 1953). Recent work between Narracoorte and Robe suggests that at least twenty major high sea level stands have occurred over the last 690,000 years (Cook *et al.* 1977). Periodic readvance was also found in South Australia.

Earth movements also occurred in the Gambier Embayment in southwestern Victoria during the Pleistocene and include both broad epeirogenic movement and local deformation associated with vulcanicity (Boutakoff 1963, Kenley 1976). In South Australia, Pleistocene uplift has been attributed, in part, to movements associated with Mt. Gambier and Mt. Burr volcanic activity (Cook *et al.* 1977).

In the Warrnambool-Port Fairy district a sequence of marine and aeolian sediments, possibly deposited over the last 700 000 years, and incorporating three glacial and three interglacial

periods has been proposed (Gill 1967, 1976, Gill & Gill 1973). Tectonic stability during the Quaternary was assumed. However the sequence encompasses three volcanic events, namely extrusion of the Yangery Basalt (1 950 000 yr), the Woodbine Basalt (300 000 yr) and the Tower Hill Tuff (c. 4000 to 7000 yr). The area also straddles the Warrnambool High, over which there is marked thinning and facies variation in certain of the Late Cretaceous and some Tertiary formations (Spencer-Jones *et al.* 1971, Taylor 1971, Abele *et al.* 1976).

There is no doubt that the Warrnambool High and its flanking troughs were tectonically initiated and it seems likely that earth movement has continued, although spasmodically to the present. Further support is provided by Leslie (1966), who pointed out that the area coincident with the subsurface ridge is geomorphically distinct, being better drained than the plains to the east and west.

At Peterborough, 30 km to the east, the Mid Miocene Port Campbell Limestone has been warped into a broad syncline, the axis of which coincides approximately with Curdie's Inlet. This



was first indicated by Wilkinson (1865) and recently confirmed from dips observed in the shore platforms. The area however, also provides evidence of earth movement of more recent date. Quaternary coastal deposits and landforms have been known here for some time. Gill (1947) noted a platform carrying marine deposits at 3.7-4 m above present mid-tide level at Flaxman's Hill, west of Peterborough, and deposits resting on a 3 m platform at Two Mile Bay near Port Campbell have been described by Baker and Gill (1957) and Ollier and Joyce (1973). The most continuous Quaternary marine section however forms the upper part of the cliffs immediately south-east of Curdie's Inlet and shows thin beds of shallow water calcarenite resting on planar surfaces on Tertiary mottled clays which contain a variably eroded upper buckshot layer (Fig. 3). Two such surfaces are present, an upper one dipping westwards at a very low angle ( $0.3^\circ$ ), and a lower one dipping at  $0.5^\circ$ W which terminates the higher surface at about 22 m above the contemporary shore platform (m.s.l.). The calcarenite forms a persistent layer on the steeper surface down to an elevation of about 8 m. The present cliff then drops to an emerged shore platform lying at 4.5 m above m.s.l. The calcarenite on the upper surface wedges out towards the east and is preserved where it is covered by aeolianite. The red-brown, slightly calcareous dune sands, which further east rest directly on the Tertiary clays, also partly mask the aeolianite and are regarded as being younger. West of the aeolianite ridge, highly calcareous dunes cover the calcarenite, and are succeeded at the western end of the section by younger dunes.

West of Peterborough (Loc. 2, Fig. 2) there is a well-developed platform at +7 m carrying up to 3.5 m of well-bedded shelly sands and associated shell beds. There is also a lower platform at about +5 m. On the adjacent cliff top, and also at Peterborough, calcareous red-brown dune sands rest on Tertiary clays, but at a lower level than those at Loc. 3 (Fig. 2), (14-15 m) and on a surface dipping east towards the Curdie Syncline. Further to the west again (Loc. 1, Fig. 2), calcareous marine burrowed silty sands occur at about +34 m, and red-brown dunes similar to those at Localities 2 and 3 are also present.

At Point Hesse (Loc. 4, Fig 2) marine shallow-water calcarenites also occur at about the same height (+31 to +35 m).

Two points are of particular interest. Quaternary deposits and forms which can be attributed directly to marine activity are limited to a very narrow strip adjacent to the present coast.

Secondly, the red-brown dunes occur at different levels on surfaces which slope towards the axis of the Curdie Syncline. If sea levels rose to the heights indicated by the marine deposits, Curdie's Inlet would have expanded to become a large embayment with a string of shoals and possibly sand bars separating it from the open ocean. The water in the centre would have been about 35 m deep at the time of highest sea level, shallowing towards the marginal terraces. Deposits in the Curdie Depression however consist predominantly of clays and sandy clays typical of the present river floodplain and swampy inlet margins. No marine deposits have been found inland from the coastal strip.

It is therefore suggested that the marine deposits were formed close to present sea level and that the whole area has been subject to uplift, that to the east (Paaratte) and to the west (Flaxman's Hill) being greater than in the axis of the Curdie Syncline. At each stillstand a broad flood plain would have formed, successive uplift and subsequent erosion resulting in flights of lateral terraces. This proposal does not exclude the possibility of eustatic sea level changes, but the alternative that the marine deposits are the result of sea levels much higher than at present and that the Curdie Depression has been formed by subsequent downwarping appears unlikely. Nor does extensive erosion following each drop in sea level explain the existence of this broad valley as the sediments carrying the lateritic Timboon Pedoderm have not been deeply enough dissected and the younger deposits on the terraces are quite thin.

The age of the Quaternary marine deposits in this area is speculative. The Two Mile Bay deposits are beyond the range of  $C^{14}$  dating (Baker & Gill 1957) but, like the deposits at Loc. 2, they contain *Ninella torquata* which has been dated at several points further west. At those points it appears to indicate an age in the range 100 000 to 125 000 yr. B.P. (Gill 1976).

## SEA LEVEL AND PLATE TECTONICS

Plate tectonics may influence sea level in two ways, firstly by changing the form of the Earth's crust, thereby producing tectonoeustatic changes, and secondly by changing the elevation of the continental margin relative to the sea. A maximum eustatic rise of 300 m (260 m related to sea floor spreading and 60 m to glacial melting) in the Mid Miocene has been suggested by Fleming and Roberts (1973). They pointed out that, if this were so, all Mid Miocene marine features now above 300 m would have attained their position by uplift. The implication as far as Victoria is concerned is



that the entire Mid Miocene marine transgression, and the subsequent regression, could be accounted for eustatically without the intervention of local tectonics. The maximum fall in sea level suggested was 800 to 1000 m in the Mid Miocene indicating that the continental shelves and the upper parts of the slopes would have been subject to subaerial influences at that time. In Gippsland the Early Miocene to Mid Pliocene sequence appears to be essentially conformable, although James and Evans (1971) and Hocking, *et al.* (1976) describe an Early Miocene slump zone, the formation of which was attributed to the reactivation of the Foster Fault system (Fig. 1). Later in the Miocene several "submarine channels" were produced, attributed to structural movements and associated sea level changes, although the precise nature of these was not specified.

In general, where the edges of continents are near plate margins, large scale earth movements may be expected (Curry 1965). These are likely to decrease away from the plate margins but complete stability must be questioned anywhere (Komar 1976). The effects on continental margins are expected to depend on the nature of the plate boundaries. Inman and Nordstrom (1971) for example, suggest that there is a close correspondence between the main morphological and plate tectonic features of coasts. Thus, the east coast of Australia, including eastern Tasmania and the Victorian coast east from Port Phillip is mapped as a collision coast, which is supposed to be characterised by a continental shelf less than 50 km wide, by coastal mountains more than 300 m high, and by a rocky, cliffed shore zone with occasional pocket beaches. When collision ceases, these coasts become maturely eroded and hilly, rather than mountainous. The coast west of Port Phillip is regarded as a trailing edge coast, that is it lies on the non-collision side of the continent and is supposed to be actively modified by the depositional products and erosional effects from an extensive area of high interior mountains, in this case the Murray drainage basin. This is the "wide-shelf plains coast" typified by low-lying coastal plains, a wide shore zone, and barrier beaches. Some features of these coasts would fit some of Inman and Nordstrom's criteria, but the correspondence is not close, as will be seen from the tectonic subdivision of the coast discussed in the next section. The Victorian coast, at least as far west as the Dartmoor Ridge, certainly appears to be anomalous in terms of their classification.

Ollier (1978) has pointed out that earth movement in the highlands of south-eastern Australia

has been dominantly vertical throughout Cainozoic time. The block structures of southern Victoria fit this concept although a complication is the marked kink in structural trends (Harrington *et al.* 1974) which suggests some east-west slip between Victoria and Tasmania. Cainozoic trends in Bass Strait, however, indicate that general foundering coupled with differential internal block movements, were dominant during that time.

While agreeing with Ollier that no pattern of drift, or current plate tectonic theory, can adequately explain the age, orientation or structure of the Eastern Highlands, there is the possibility that northerly drift of the Australian plate has resulted in rifting between Victoria and Tasmania. Assuming that the Australian plate is drifting northwards, southern Australia becomes the trailing edge, and tension normal to the direction of plate movement might be expected, resulting in the detachment of crustal fragments. Thus, Tasmania could be in the process of splitting off from the mainland. This would have far-reaching effects on relative sea levels in and adjacent to the rift zone.

## CONTRASTS IN COASTAL SEGMENTS

Victorian coastal configuration is dominated by two factors, namely the direction of swell approach (Bird 1961) and the tectonic style.

The effect of the dominant swell can be traced back to the Mid Tertiary at least, producing two segments of contrasting coastal orientation separated by the Bassian Rise (Jennings 1959), represented on land by Wilson's Promontory.

To the east of the Bassian Rise, south-easterly swell is dominant, while to the west, a south-westerly swell dominates. At present, there is some interaction between the two in eastern Bass Strait but during very low sea levels in the Late Quaternary and possibly the Miocene, the Bassian Rise would have been a land area dividing Bass Strait from the Tasman Sea and preventing swell interference between the two. The effect is shown by the orientation of both Quaternary and Late Tertiary barriers and other wave generated shore line features (Figs 1, 4), which face the direction of the refracted wave approach.

The tectonic division, however, is the Dartmoor Ridge far to the west (Fig. 1). In the Gambier Embayment, west of the Dartmoor Ridge, the Pleistocene sea extended inland to the Kanawinka escarpment (Kenley 1976), but to the east it did not reach far beyond the present coast. West of the Dartmoor Ridge the dominant fault trends are NW to NNW (Spencer-Jones *et al.* 1971) while to



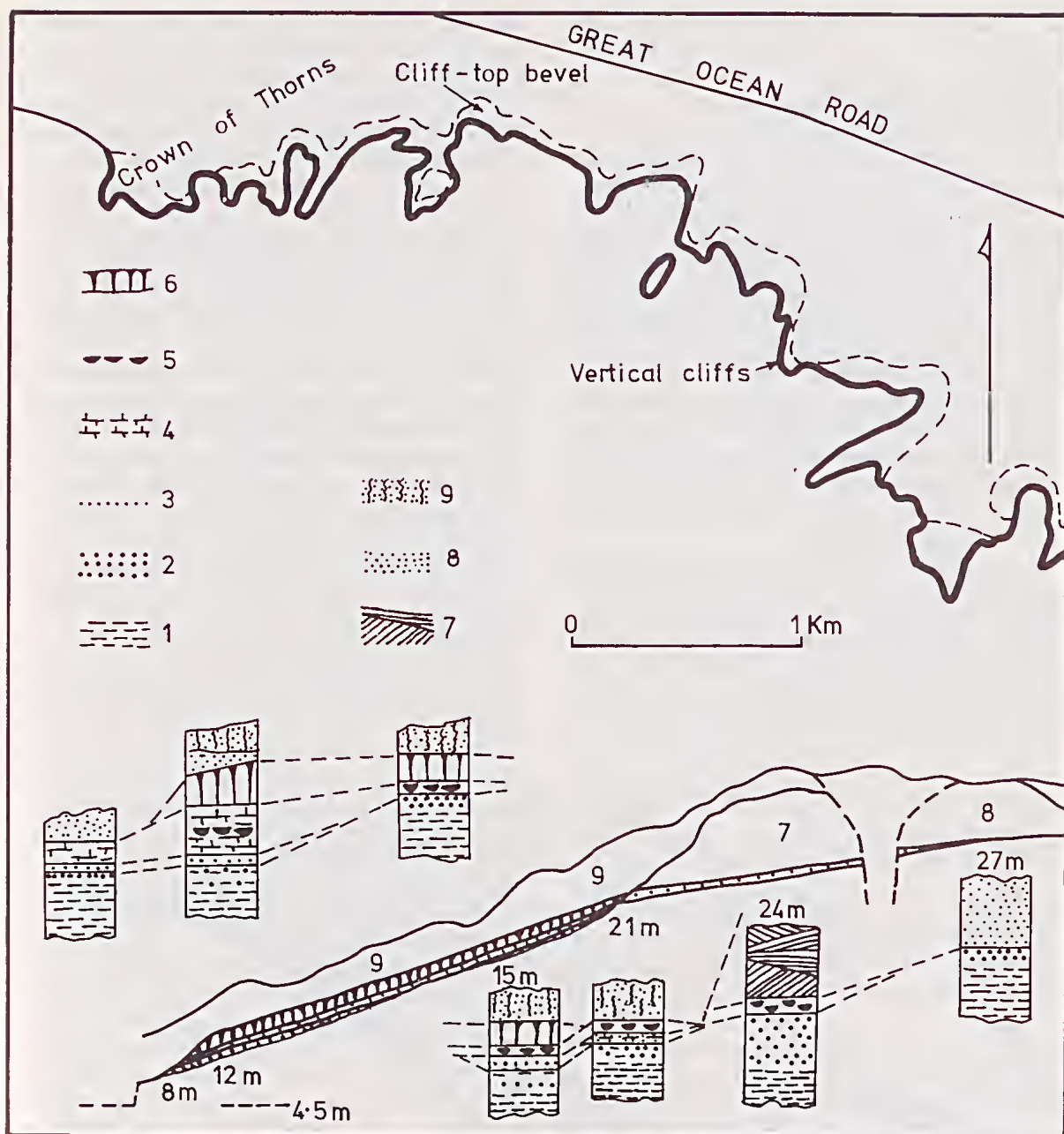


FIG. 3—Crown of Thorns area, east of Peterborough:

1—Mottled clay (Pliocene); 2, Buckshot, *in situ* and reworked; 3, Calcareous sand; 4, Bioturbated calcarenite; 5, Scoured calcarenite; 6, Calcareenite with vertical burrows; 7, Aeolianite; 8, Red-brown dune sands; 9, Calcareous dune sand with abundant rhizomorphic concretions.

the east they are N to NE, with east-west trends becoming conspicuous E of Wilson's Promontory (Fig. 1).

In the Gambier Embayment the main structural trends are oriented in a similar direction to the refracted wave fronts, while on the remainder of

the coast the two lie at an appreciable angle. A broad embayment with an extensive series of parallel barriers is characteristic of the first condition. In the second there is a succession of alternating headlands, truncated plateaux and relatively small embayments along the coast, pro-

viding a framework for highly varied local coastal development.

#### SEA LEVEL FLUCTUATION AND INSTABILITY OF THE LAND

Tindale (1933) considered the possibility of eustatic variations in sea level, and their correlation with European glacial phases in connection with raised strandlines in South Australia. Similar suggestions were made in Tasmania by Lewis (1935) and Edwards (1941). In Victoria, Hills (1940) systematically examined the problem of eustatism and tectonics and pointed out that shell beds then designated as Recent and since shown to be so by  $C^{14}$  dating, lie at different elevations above sea level. Hills concluded that at least part of the emergence was due to tectonic uplift. At the same time he suggested that, as evidence of Recent emergence was so common, a eustatic fall in sea level was a likely contributor.

The succession of so-called dune ranges and raised beaches in South Australia has attracted particular attention (Crocker & Cotton 1946, Hossfeld 1950, Sprigg 1948, 1952). Sprigg (1952) attempted to correlate the high sea levels (raised beaches) with the Mediterranean sequence as defined by Zeuner (1945) and with the

Milankovitch (1938) radiation peaks. He showed that the dune ranges had been tilted towards the west, the older dunes being tilted at a greater angle than the younger. Boutakoff (1952) noted the continuation of Pleistocene strandlines into Victoria. They are also tilted towards the west and fan out in a westerly to north-westerly direction from the Portland area which was regarded as being tectonically stable (Boutakoff 1963). Direct correlation with the European (mainly Alpine) chronology was attempted, equating features around Portland with the Pleistocene glacials and interglacials.

Until recently this supposed relationship has strongly influenced most workers in this field in Victoria (Gill 1967, 1971, 1976, Ward & Jessup 1965, Jenkin 1968, Ward 1966). Ward *et al.* (1971) proposed a correlation of features, interpreted in Gippsland as former shorelines, with marine terraces in South Carolina and Ward (1977) also linked Holocene shorelines in Gippsland, after allowing for uplift, with those in the Firth of Thames, New Zealand.

There is general acceptance that climatic fluctuations causing glacial advance and retreat result in corresponding changes in sea level, and a more credible, positively datable sequence of these

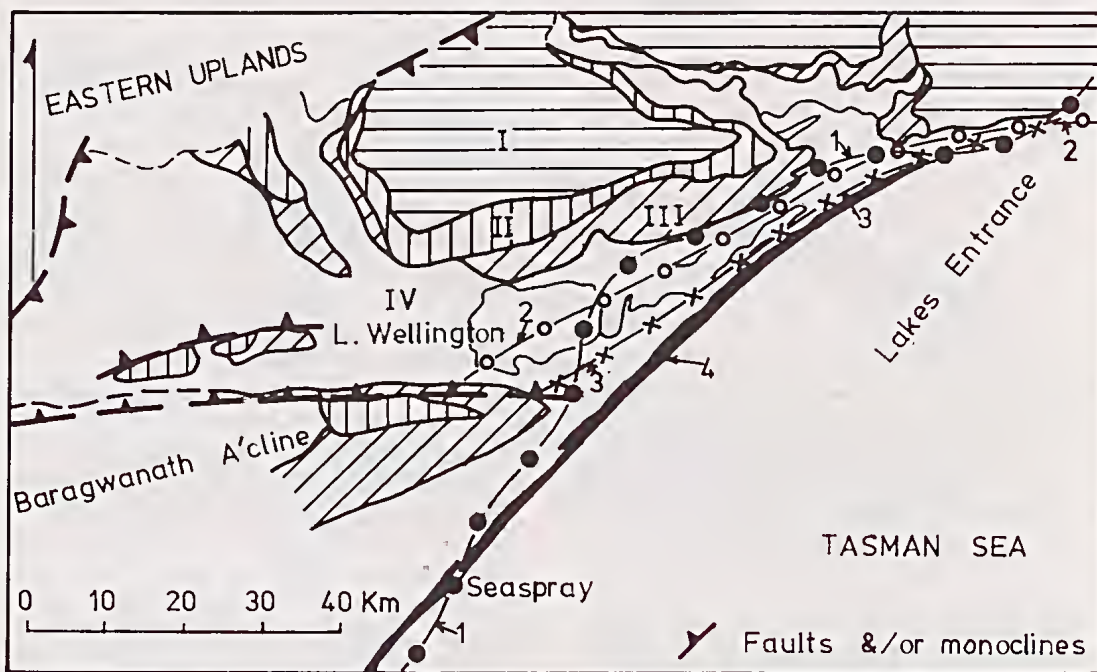


FIG. 4—The Gippsland Lakes area:

I, II, III—High-level benches, ?E. to M. Pleistocene; IV, Late Pleistocene delta complex; 1, Possible Pliocene barrier; 2, 3, Late Pleistocene barriers; 4, Outer (Holocene) barrier.



events on a world-wide scale seems now to be emerging. This is essential if the relative significance of eustatic and tectonic factors is to be reliably evaluated.

Oxygen-isotope study of deep sea cores, where sedimentation is likely to have been continuous and to reflect oceanic temperature changes, has produced a succession of stages which, coupled with magnetic measurements and  $C^{14}$  dating, can be used to date climatic changes over the last 850 000 years (Shackleton & Opdyke 1973). The 16 metre equatorial Pacific core showed 23 isotope stages, the nineteenth stage coinciding with the boundary between the Brunhes and Matuyama magnetic epochs, which has been dated at 700 000 years. Cores from the Southern Ocean show some significant differences from the equatorial sequence where distinct fluctuations indicated by the Antarctic core are obscured in the tropical core by sediment disturbance due to burrowing organisms, particularly in Isotope Stage 5 (Hays *et al.* 1976, Shackleton 1978).

Other approaches include plotting carbonate abundance (Frakes 1978) and the abundance of temperature-dependent radiolaria and foraminifera (Keaney & Kennett 1972). Frakes showed that in the Brunhes magnetic epoch, that is, over the last 700 000 years, cold intervals are more regular, more closely spaced and better defined than in the Matuyama epoch, that it is generally cooler, and that there seems to be a trend towards generally warmer conditions over the last 450 000 years.

Dating of emerged coral terraces has also thrown light on changes in sea level. In New Guinea, Chappell (1974) examined a series of clearly-defined terraces progressively uplifted tectonically to a maximum height of more than 600 metres. Radiometric dating of shallow water coral faunas showed nine periods of high sea level going back 20 000 years. It was also shown that, if a uniform rate of uplift was assumed, the high sea level stands were mostly below present sea-level. More recently Chappell and Veeh (1978) have confirmed these results, with extrapolation back to 700 000 years B.P., in North Timor and at Atauro Island. They point out the closeness of the correlation between the main periods of glacioeustatic rise and those indicated by the oxygen isotope profiles from Pacific cores.

There appears to be sufficient agreement between the curves produced using the various techniques now available, despite some discrepancies, to lend encouragement to the view that a reliable chronology of events during the last few million years may soon be developed.

## NEOTECTONICS

Relief-forming movements of the earth's crust are described as neotectonic (Bondarchuck *et al.* 1959). There is no doubt that neotectonic movements have occurred in Victoria as was shown by Boutakoff (1963) and Kenley (1976) in south-western Victoria, Hills (1940) in the Port Phillip Sunkland, and Boutakoff (1955) and Jenkin (1968) in south-east Gippsland. Undoubted neotectonic effects have been recognised inland (Bowler 1978, Bowler & Harford 1966) and it is thought that the phenomenon has been significantly under-estimated in south-eastern Australia. Recent work in the Peterborough-Port Campbell area (above) suggests appreciable Quaternary movement and Bird (1965) has suggested that uplift at the intersection of the Rosedale Fault and the coast has initiated barrier formation in the Gippsland Lakes area.

## REGIONAL AND LOCAL EARTH MOVEMENT

On several parts of the Victorian coast there is definite evidence of emerged Holocene shell beds and the apparent diversity of tectonic environments for these occurrences has been relied upon previously in attempts to establish the existence of Holocene sea levels higher than the present level (Gill 1971, Jenkin 1968).

The history of south-eastern Australia through the Cainozoic seems to have been one of general uplift, accompanied by differential block faulting, particularly in the Eastern Highlands province (Ollier 1978), but varying in intensity, as proposed by Wellman (1979). It is suggested here that apparent Holocene still stands above the existing sea level can be adequately explained by such earth movements.

The precise tectonic effect, however, would vary with the tectonic pattern and the level of activity. Emerged Holocene shell beds in Victoria are in a region which appears to be tectonically active compared with the sections of eastern Australian coast studied by Hails (1965), Hails and Hoyt (1968), and Langford-Smith and Thom (1969). A possible exception is shown by work in the Shoalhaven valley of the South Coast (Walker 1958, noted by Langford-Smith and Thom (1969). This occurrence, like those in Victoria, is in what appears to be a more tectonically active section than are the Holocene deposits further north.

Successions of older raised shorelines have been recognised in New South Wales (Hails & Hoyt 1968) and Victoria (Gill 1967b, Jenkin 1968). As pointed out previously, those in the Gambier Em-



bayment (Kenley 1971) are unique as far as Victoria is concerned and will be considered separately.

The recorded levels (m) are:

| NSW     | Gippsland | Warrnambool-<br>Port Campbell |
|---------|-----------|-------------------------------|
| 1.6-3   | 3.3       | 3                             |
| 3.7-4.5 |           | 3.7-4<br>4.5-5                |
| 6-9     | 8         | 7.5<br>8.5                    |
| 12-15   | 15        | 10.5<br>21                    |
| 24-30   | *         | 23.5<br>28<br>31              |

\* Higher levels have been proposed for the area north of the Gippsland Lakes (Jenkin 1968, Ward 1977). However, an alternative origin for these features is suggested below.

On present information, no direct correlation of the observed levels is feasible, principally because little accurate dating has been done and insufficient precise longitudinal topographic data are available regionally. Nevertheless, there is sufficient information from certain critical areas on which to base some generalisations. Dating of corals from the Inner Barrier at Evans Head on the north coast of New South Wales for example has given ages between the limits of  $112\,000 \pm 9\,000$  and  $127\,000 \pm 18\,000$  years, the deposits being related to a sea level of 4 to 6 metres above the present mean. Dates obtained from Newcastle Bight ( $142\,000$  and  $143\,000 \pm 12\,000$  yr BP) could be related to a previous transgression. No definite older marine deposits at higher levels were found and it was inferred that the sea returned approximately to the Inner Barrier level at each period of high sea level which occurred during the past 700 000 years (Marshall & Thom 1976). Stranded marine deposits, undoubtedly older than dated Holocene shell beds, have been recorded from various parts of the Victorian coast. Shells from the Port Fairy Calcarene, which is related to a mean sea level of about 7 m, have been dated at 125 000 BP (Gill 1967, 1976). An earlier high sea level is indicated by the Sunnyside Sand, shells from which gave a date of about 400 000 yr BP (Gill & Amin 1975).

The well-preserved, but mostly disconnected occurrences of undoubted pre-Holocene shore zone sediments in the adjoining Peterborough-Port Campbell area have not yet been dated. However, despite undoubted tectonic effects, they also in-

dicate sea level fluctuations. The 7 m platform at Loc. 2 (Fig. 2), which carries at least 3.5 m of Pleistocene sub-aqueous sediments, is obviously an inherited feature. The 3 m platform at Two Mile Bay (Loc. 5, Fig. 2) could also belong to this category.

Pre-Holocene shoreline deposits above present sea level are rare in the Port Phillip area. Exceptions are the aeolianites of the Nepean Peninsula and Queenscliff, the shelly sediments at Portarlinton (Jutson & Coulson 1937) and the Picnic Point deposits at Hampton (Gill 1950). The only shoreline deposits which are now at a high level are those at the eastern end of the Nepean Peninsula, where they are thought to have been uplifted by movement on Selwyn's Fault (Jenkin 1968). As tectonic stability cannot be assumed for Portarlinton and Hampton, there is no undoubted evidence in Port Phillip for Pleistocene sea levels above the present.

In Western Port there is no evidence of Quaternary marine or shoreline sediments older than Holocene (Marsden & Mallett 1975). It is likely that, during the Late Pliocene, and certainly during the Pleistocene, Western Port was gradually subsiding, but that no Pleistocene sea level was high enough to inundate any part of the area. Western Port is thought to have been cut off from the ocean by barriers behind which were swampy lowlands and shallow lakes, the associated deposits being represented by sands, sandy clays and clays at Woolamai Beach, Cat Bay, Flinders and possibly north-west French Island and Warneet (Jenkin 1962). In both Port Phillip and southern Mornington Peninsula also, deposits of fresh or brackish-water limestones occur in valleys whose drainage was probably impeded by barrier or estuarine marsh development.

In south-eastern Gippsland, retreat from the Mid Miocene maximum marine advance is indicated by the regressive late Miocene Tambo River Formation (Carter 1964). Regression continued in the Pliocene, except in the Alberton-Welshpool area where a local readvance, probably related to downwarping, has been recorded. The occurrence of barriers and lagoons with successive marine, brackish, then freshwater deposition as the sea retreated through the Pliocene in the Gippsland Lakes area, foreshadowed by Jenkin (1968), has recently been confirmed and elaborated by Carter (1979). These deposits were finally over-run by the dominantly terrestrial Haunted Hill Gravels which are variably exposed on the coastal plateau, as it was termed by Bird (1961), north of the Gippsland Lakes.



The plateau is benched and carries sand ridges of varying form and height. Two of these benches were interpreted by Jenkin (1968) as representing Mid Pleistocene sea levels. Ward (1977) subsequently accepted a marine origin for these features and extended the sequence, thus:

| Jenkin (1968) |       | Ward (1977)       |
|---------------|-------|-------------------|
|               | 8 m   | Late Pleistocene  |
|               | 11 m  | (younger)         |
| 27-30 m       | 20 m  | Late Pleistocene  |
|               | 21 m  | (older)           |
| 33-36 m       | 38 m  | Mid Pleistocene   |
| >36 m         | 49 m  |                   |
|               | 79 m  | Early Pleistocene |
|               | 110 m |                   |
|               | 128 m |                   |

The discrepancies in levels, up to about 6.5 m, appear to be mainly due to the different criteria used. Jenkin used the general level of the bench at the inner break of slope whereas Ward used specific levels requiring interpretation of various sedimentological and morphological features, viz. highest beach level, highest well-sorted sediments, level of tidal marsh, lowest undissected land inland of shore. A major difficulty with the marine bench hypothesis is that no undoubted marine deposits have been found on them. Because the scarps face SSE towards the sea and join undoubted fluvial terrace facets at a very sharp angle, they were presumed to be marine. It was also suggested that many of the sand ridges associated with the benches could best be interpreted as coastal barriers and submarine bars (Jenkin 1968). Ward (1977) does not accept that any of these ridges are submarine in origin, but rather that they represent shoreline deposits stranded during coastal retreat.

An alternative to a direct marine origin for the benches and their surface features involves successive fluvial, deltaic and aeolian deposition with contemporaneous development of a coastal barrier sequence, coupled with earth movements of two kinds. It has been suggested that, in the Gippsland Lakes area, Late Pleistocene flood plain, delta flood plain and barrier features form a more or less contemporaneous depositional complex (Jenkin 1968). The later discovery of shell beds, dated at 101 000 yr BP (Schornick 1973), lateral to a supposed deltaic stream levee, helps to confirm this environmental reconstruction. Streams entering the Latrobe Depression at this time were diverted towards the east into lagoons

or lakes behind the Inner, or Prior, Barrier. A broadly similar situation applies at the present time, and it is also suggested that these conditions could have been operative intermittently through the earlier parts of the Pleistocene, and back into the Tertiary.

Work of Jenkin (1968), on the earlier Pleistocene, and of Ward (1977) may be reinterpreted and, instead of viewing Tertiary conditions as being essentially different from those of the Pleistocene, and Holocene, definite although complex repetitions can be identified. Thus, the benches on the coastal plateau possibly represent a succession of delta flood plains formed in tectonically stable periods between intermittent episodes of differential earth movement. Coastal plateau rise coupled with depression on the Latrobe axis seems to be a necessary accompaniment, otherwise Pleistocene marine or estuarine deposits would occur far inland to at least 40 km beyond their known limits.

The higher level cliffs, previously regarded as marine, are therefore interpreted as fluvial, the sandy ridges as levee and channel deposits, which have suffered some aeolian reworking, with source-bordering sand dunes which tend to be concentrated at the major breaks of slope between one terrace and another. Swamps and other extensive poorly drained areas, which are common on the flats between the sandy ridges, would then be interpreted as delta flood plain swamps (Figs 4, 5).

In the contrasting south-western sector of the Victorian coast, the succession of calcareous dune ridges extends from the Kanawinka scarp to the present coast and is regarded as covering most of Pleistocene time (Kenley 1971, 1976). Kenley pointed out evidence, in the truncation of some dunes, of periodic readvance of the sea, and as already mentioned, the ridges are tilted towards the north-west.

In the contiguous region of South Australia, a recent detailed traverse (Cook *et al.* 1977) has also indicated that uplift during the Pleistocene, combined with eustatic sea level changes, has produced an essentially regressive sequence resulting in a seaward progradation of about 100 km during the last 690 000 years. It was also shown that periodic readvance occurred and that the Pleistocene earth movements were partly related to the Mt. Gambier-Mt. Burr volcanicity. The last point has been largely neglected as far as Victoria is concerned but it is reasonable to expect that the late Quaternary highly explosive, although short-lived activity, such as that around Warrnambool,

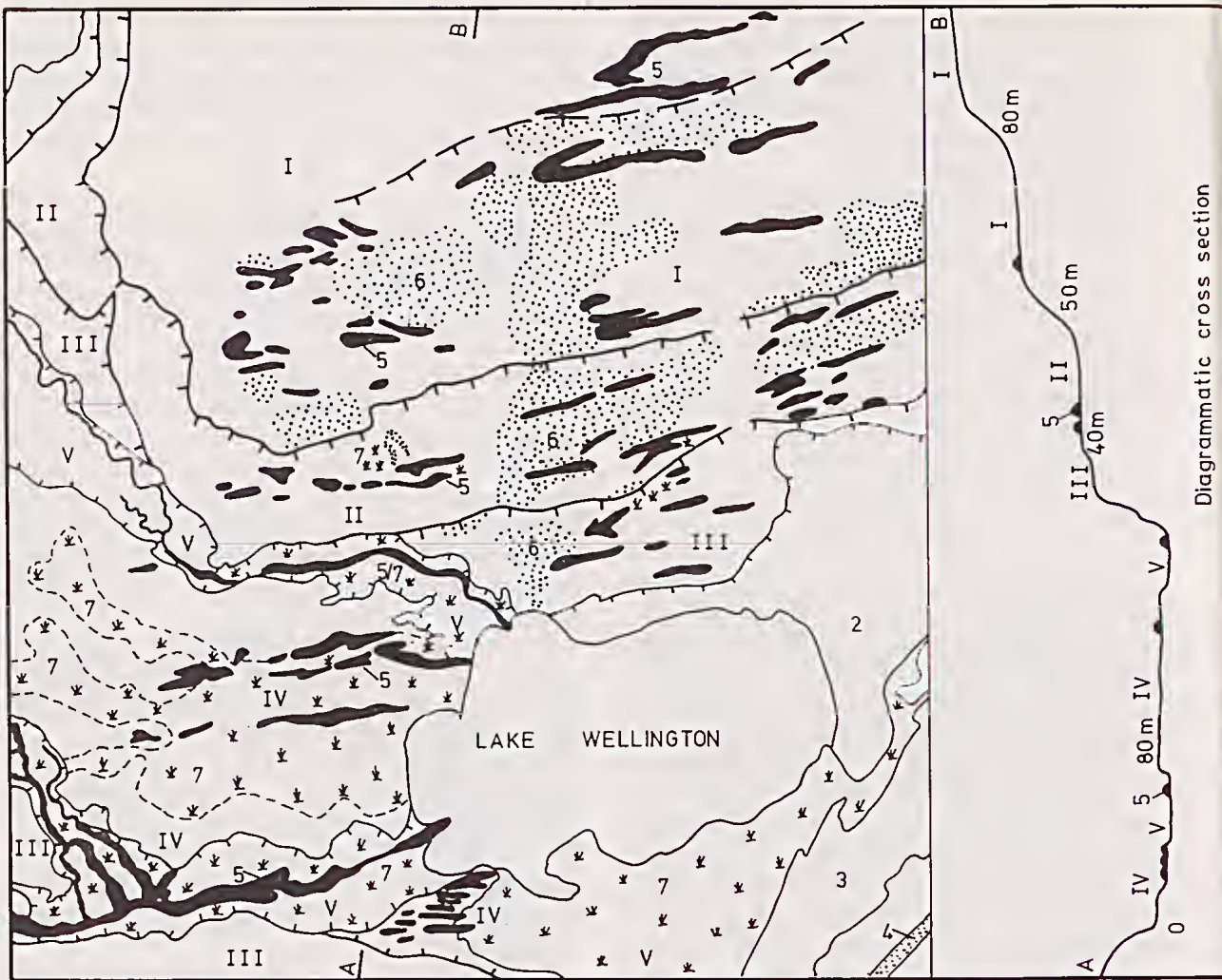


FIG. 5—Terrace sequence near Lake Wellington, East Gippsland:

I to IV, and 1 to 4—as in Fig. 4; V, Contemporary flood plains and back swamps; 5, Contemporary levees and probable Pleistocene levees; 6, Sand ridges, hummocks and sheets of various ages and origins; 7, Swamps.

North is to the right. Section A-B is about 40 km.

as well as earlier Pleistocene volcanic events, for example the extrusion of the Yangery (1 950 000 yr BP) and Woodbine (300 000 yr BP) Basalts, would have resulted in some earth movement. In broader terms, the remarkable coincidence of the Australian Cainozoic volcanic provinces with the overall tectonically positive Eastern Highlands (Ollier 1978) and, specifically, the late Cainozoic “areal” province of Victoria and South Australia, suggests a general association with uplift.

Further evidence of vertical uplift during the late Quaternary comes from Tasmania where marine deposits, dated as “Last Interglacial”, that is during the last period of high sea level before the Holocene marine transgression, and aged by reference to their relationship with  $C^{14}$  dated non-

marine deposits, lie at 20 to 30 m above present sea level. This is 10 to 20 m higher than deposits of similar age in supposed stable areas in Australia (Van de Geer *et al.* 1979).

## CONCLUSIONS

The history of the Victorian coast can be traced back to the Late Cretaceous, but it is only from the Mid Miocene onwards that it can be documented in any detail. The coastal zone has continually migrated back and forth within the region lying between the continental slope and the upland front.

The coastal zone has been subject to sea level fluctuation, probably both glacio- and tectono-eustatic, and to broad crustal warping coupled



with local differential earth movements. In Victoria there seems little doubt that eustatic and tectonic factors have both been involved in variations of apparent sea level at any particular site. No area can be assumed to be tectonically stable, even within the broad limits imposed by the largest suggested Quaternary high sea level.

Sequences of Quaternary sea level changes and coastal stratigraphy, for example those developed in Europe and North America, should not be regarded as standard sections into which local occurrences must be fitted. Recent work on deep sea cores and on the dating of raised coral reefs promises to produce a standard sequence of wide applicability. A reliable standard such as this is necessary in the evaluation of tectonic effects on both regional and local scales.

The Tertiary is characterised by coastal advance until the Mid to Late Miocene, followed by regression during the remainder of the period. In detail, both trends included lesser marine incursions and regressions. These fluctuations were not uniform everywhere, being influenced by local structure, by tectonic activity and by the magnitude and direction of regional supergene forces.

Except in far south-western Victoria, it is probable that the Quaternary coast has rarely, if ever, been located inland far beyond the present shore. To explain this limitation, in the light of the elevation of undoubted Pleistocene marine sediments, uplift in some areas of at least 30 m is required.

On the southern Australian coast Holocene shell beds have undoubtedly emerged, but there are no equivalents on the northern NSW or southern Queensland coasts, showing that differential earth movement has been involved.

But this, in itself, does not indicate the sense of the movement. It seems that the south was more tectonically active than the north, suggesting that the southern Australian Holocene stranding was due to tectonics rather than a fall in absolute sea level. Although local earth movements appear to be mainly vertical, east-west transcurrent movement between Victoria and Tasmania is possible.

Certain features in south-eastern Gippsland, previously attributed to shallow marine and shore zone activity, can be interpreted as fluvio-deltaic erosional and depositional forms. Despite this, they would have formed close to their contemporary sea level, which implies that this level must have been, at some stage in the Early Pleistocene, at least 80 m higher than at present, that the land has been elevated by a similar amount, or that both effects, while of lesser magnitude, acted in concert.

Ridges associated with late Tertiary shorelines are not confined to the north-west and have been identified with reasonable certainty in several parts of southern Victoria. In some areas, distinct parallelism of lateral drainage is thought to have been controlled by stranded coastal ridge and trough terrain.

Many problems regarding Victorian coastal evolution remain to be solved. The principal future needs include absolute dating, to the stage when the reliability of dates for critical horizons is established, detailed studies of sedimentary facies and associated landforms over the whole of the coastal zone as it migrated through time, and a reliable stratigraphic scale with which to compare local sequences. In addition, accurate, detailed and repeated altimetric surveys are required to determine the precise levels of features described or dated and to detect neotectonic movements, which are likely to be significant along coasts such as those of south-eastern Australia.

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